ARMY RESEARCH LABORATORY

Modeling and Analysis of a 3-D Asymmetric Mine-Soil-Hull Floor Interaction Problem With Mine Buried in Dry and Wet Sand

by Aaron D. Gupta

20010927 078

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

Modeling and Analysis of a 3-D Asymmetric Mine-Soil-Hull Floor Interaction Problem With Mine Buried in Dry and Wet Sand

Aaron D. Gupta
Weapons and Materials Research Directorate, ARL

Abstract

An above-ground 2.44 m × 2.44 m × 20 cm rolled homogeneous armor (RHA) plate with a total mass of 9000 kg located asymmetrically at a fixed horizontal 61 cm offset and a vertical 46 cm stand-off above a shallow-buried mine with an equivalent charge weight of 9.05 kg TNT and 15 cm depth of overburden in dry and wet sand has been modeled in 3-D using the CTH hydrodynamic code. The purpose is to compare the loading and response of the anvil plate due to detonation of a mine buried in dry and wet sand using a 3-D asymmetric model of a mine-soil-hull floor interaction problem. The model allows parametric study of complex explosive-soil-structure interaction effects due to variation of explosive types and plate dimensions, standoff, types of soil and height of soil overburden and computes momentum loading on the ballistic pendulum anvil plate due to various off-axis locations of the mine in dry and wet soils relative to the hull floor plate located on the underside of an armored vehicle.

MODELING AND ANALYSIS OF A 3-D ASYMMETRIC MINE-SOIL-HULL FLOOR INTERACTION PROBLEM WITH MINE BURIED IN DRY AND WET SAND

Aaron D. Gupta
Mechanical Engineer
U.S. Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066.

ABSTRACT

An above-ground 2.44 m x 2.44 m x 20 cm rolled homogeneous armor (RHA) plate with a total mass of 9000 kg located asymmetrically at a fixed horizontal 61 cm offset and a vertical 46 cm stand-off above a shallow-buried mine with an equivalent charge weight of 9.05 kg TNT and 15 cm depth of overburden in dry and wet sand has been modeled in 3-D using the CTH hydrodynamic code. The purpose is to compare the loading and response of the anvil plate due to detonation of a mine buried in dry and wet sand using a 3-D asymmetric model of a mine-soil-hull floor interaction problem. The model allows parametric study of complex explosive-soil-structure interaction effects due to variation of explosive types and plate dimensions, standoff, types of soil and height of soil overburden and computes momentum loading on the ballistic pendulum anvil plate due to various off-axis locations of the mine in dry and wet soils relative to the hull floor plate located on the underside of an armored vehicle.

INTRODUCTION

Both armored personnel carriers and light combat vehicles are increasingly being used in a support role for other, more heavily armored combat vehicles, all of which are being subjected to much greater risk from a variety of highly lethal antitank land mines. As a result, there is a need for modeling and understanding the interaction of mine blast products with structures and the resulting loading and damage mechanisms inflicted by explosive blast and impact. This understanding is required both for damage assessment and protective hardening of both wheeled and tracked vehicles. This has been a topic of considerable interest to the U.S. Army Research Laboratory (ARL) at Aberdeen Proving Ground, MD.

An interesting study [1] involved collation of data from previous scaled experiments related to the encounter of buried land mines with various targets including flat plates. A correlation function, based on dimensional analysis, for the total impulse delivered by the land mine and overburden on a target was presented. Vulnerability of tank bottom hull floor plates subjected to shallow-buried mine blast was studied by Norman [2] and Hoskins et al. [3], who employed an approximate energy method

1

approach and equated the strain energy absorbed by the plate to the energy delivered by the blast to the armor plate based on the law of conservation of energy. Various simple models of explosively driven metal were developed by Dehn [4] and compared with experiments.

In another investigation [5], the DORF hydrocode was used to generate the loading history on a target plate subjected to a blast load from a land mine. The mine blast loading was used in a structural response code to compute the response of a clamped-edge, square rolled homogeneous armor (RHA) plate. The predicted deflection and total impulse were in satisfactory agreement with values computed using an empirical correlation function derived from field experimental data.

Dynamic response analysis of a rectangular simply supported plate subjected to an explosive blast was analyzed by Gupta [6] for the linear elastic case and compared to a closed form solution. The analysis was extended to the elastic-plastic domain by Gupta et al. [7], who employed the isotropic bilinear hardening material model available in the ADINA nonlinear finite element analysis code. This study was further extended by Gupta et al. [8] to the response of a generic vehicle floor model subjected to empirically obtained, triangular overpressure loads from the detonation of a shallow-buried mine. Although qualitative agreement with experiment for peak deflection could be obtained, the residual plastic deformation could not be compared effectively due to lack of soil loading arising from blast-soil-structure interaction, which substantially affected the estimated blast loads and the resulting structural response. Another recent study of dynamic elastic-plastic stress and deformation response of a generic vehicle floor model to coupled blast and impact loads from a plate mine was reported by Gupta [9]. He provided an inexpensive method of evaluation of the structural integrity of modern vehicles subjected to severe spatially varying transient loads in extreme environments.

A number of studies have been performed in the general area of blast response to structures over the years. However, the loading mechanisms from blast-soil-structure interaction, such as those occurring from detonation of a mine buried in saturated soil resulting in moisturized soil are poorly understood at present. The current investigation is an attempt to fill this void and to simulate loading of the anvil plate during blast-soil-plate interaction. This plate acts as a momentum trap for the impulse delivered by the mine detonation. This loading is needed for the design of the guide shaft for the Vertical Impulse Measurement Facility (VIMF), which is currently under construction at APG.

OBJECTIVE

The primary objective of this investigation is to simulate detonation of a mine buried in sand bracketed between two extremes of moisture content:—dry vs. fully saturated. The mine detonation causes propagation of the blast-soil wave upward, resulting in blast-soil-structure interaction and consequent loading of the anvil plate. The study is needed to obtain improved loading functions for combined blast and soil loading. The effect of soil moisture content upon the momentum delivered is one of the important questions to be answered. These loading data can then be transferred to a nonlinear finite element analysis code to obtain transient structural response. The predicted results can then be compared to data from experiments designed to capture and measure the loads produced

in these events. Such capability will, in turn, enable the development of models of expansion of blast/soil events in which moisture-dependent soil properties play a significant role.

Accuracy of predictive models is essential to the development of innovative vehicle designs that have improved survivability characteristics and are, at the same time, light enough to ensure rapid deployment and desired load-carrying capacity. The ultimate objective is to improve survivability of the crew in vehicles subject to land mine attacks.

PROBLEM CONFIGURATION

The problem involves the worst-case scenario of a shallow-buried cylindrical mine embedded all around in two different soil types: dry sand and wet soil with a 15-cm soil overburden. The mine contains explosive with an equivalent charge weight of 9.05 kg TNT and is asymmetrically located with a horizontal centerline offset distance of 61 cm relative to a square plate 244 cm × 244 cm. Plate thicknesses of 15 cm and 20 cm were modeled. The vertical standoff between the bottom plate surface and the top of the soil overburden was 46 cm as shown in Figure 1. The cylindrical configuration of the mine has a diameter of 32 cm and a height of 9 cm. The mine is located inside a block of soil 366 cm in diameter with a total height of 124 cm.

ASSUMPTIONS

The asymmetric configuration of the mine as defined in the previous section is a three-dimensional (3-D) problem requiring the generation of a 3-D model that may be expensive to run using a hydrodynamic code. However, simplification of the 3-D problem to a 2-D model using two-dimensional (2-D) plane strain assumptions does not work since 2-D results apply to a semi-infinite model where both the anvil plate and the explosive geometry are extended to infinity in the Z-diection contrary to the finite geometry of the real 3-D problem. The amount of explosive and the plate mass for the 2-D plane strain problem are significantly higher than those for the finite 3-D model. Additionally, loading and response predictions from CTH computation for the 2-D plane strain model cannot be easily scaled or correlated to the corresponding results from the full blown 3-D analysis. As a result, in the current analysis a finite 3-D model was employed with fixed geometry of the plate, the soil and the cylindrical mine close to actual dimensions to be employed in a test to simulate the worst case scenario.

All empty spaces between the plate and the soil block and all around these configurations were filled with dry air in the hydrocode model. The wet sand is assumed to be fully saturated due to high moisture content completely filling the void volume, which is approximately 27.4% of the entire soil volume. This ensures a worst-case scenario with significant contribution to the resultant momentum produced in the momentum trap. In the second case, dry sand with no moisture content is considered as the burial medium for the explosive. This allows bracketing of the influence of large variation of basic soil properties due to maximum possible variation of moisture content upon structural loading and response for the most commonly available soil type.
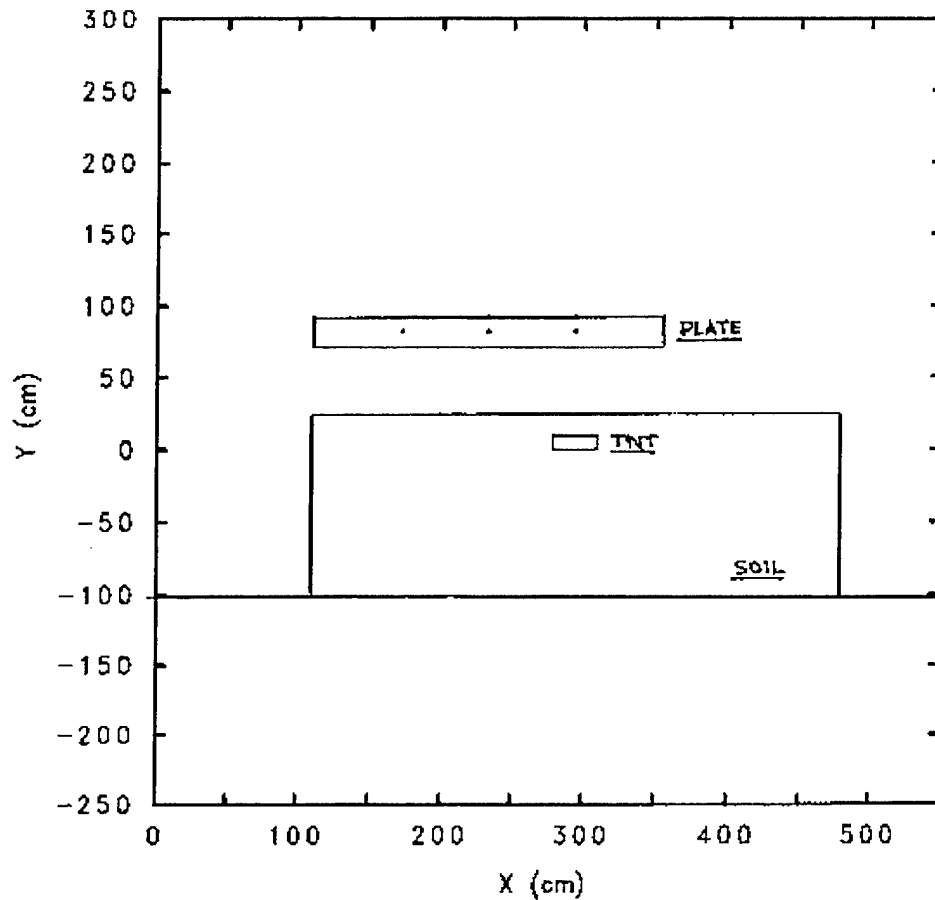
3

Figure 1. Initial Configuration of the Asymmetric Mine-Soil-Structure Interaction Problem

MODEL DESCRIPTION

A 3-D asymmetric model with a 61-cm centerline offset of the anvil plate, as shown in Figure 1, was generated for the CTH code [10, 11]. A 3-D Eulerian mesh was overlaid using uniform relatively coarse grid spacing in horizontal X, vertical Y and lateral Z directions throughout the computational space. Each cell size was a cubic mesh 2 cm × 2 cm x 2 cm, and the total number of cells was 260,000. An aspect ratio of 1.0 was maintained in computational space to ensure numerical accuracy. The problem region was extended approximately 110 cm vertically above the top plate surface and horizontally beyond the left and right geometric edges to minimize reflection from the computational boundaries. This large volume of space filled with dry air accommodated large displacements and tilt angles of the anvil plate expected to occur due to asymmetric loading from mine detonation. Computed prediction of peak vertical displacements and rotation will be useful in designing vertical guides, guide bars, and springs for the experimental test fixture.

4

BOUNDARY CONDITIONS

The steel plate is assumed to be freely suspended 46 cm above the top surface of the soil block in which the mine is embedded and is initially at rest. The bottom horizontal soil boundary 100 cm below the mine is assigned a transmitting boundary condition where mass may flow in and out of mesh but no reflection is allowed from the boundary.

Both left and right vertical, near and far lateral as well as the top horizontal boundaries of the computational mesh are assigned extrapolated pressure boundary conditions where mass is not allowed to flow into the mesh but the pressures in cells at the boundary are computed using extrapolated values from two adjacent cells. This boundary condition is mostly transmissive with some reflection permitted.

MATERIAL MODELS

The model involves four different material types. The first package in the problem setup represents the TNT explosive for the land mine. The next package represents the rolled homogeneous armor (RHA) steel plate. This is followed by the soil package surrounding the explosive. The final package refers to dry air, which is used to fill all remaining empty space between and around the previous three packages and extends up to the edges of the computational mesh.

The default SESAME tabular EOS available in the CTH [11] material library was used for RHA steel. This EOS treats the polymorphic and melting ransitions in iron, and it gives good agreement with shock wave and penetration experiments..

Initially, the Johnson-Cook [12] constitutive model for the deviatoric response behavior of steel was used, which resulted in appreciable transverse bending deformation of the steel plate. To reduce large deformation response of the steel plate, an elastic-perfectly plastic constitutive relationship with a yield strength of 1.5E09 Pa, Poisson's ratio of .285 and the Johnson-Cook fracture model with a fracture strength of -3.8E09 Pa was used..

The material model employed for the TNT explosive was the default JWL (Jones-Wilkins-Lee) equation of state available in the material library. For the detonation of the explosive, a programmed explosive burn routine designated as HEBURN in the hydrocode was employed. The initiation was chosen to start at the bottom central location on the vertical symmetry axis of the mine, and pressure contour plots were generated at a regular interval of 10-cm radius. The detonation velocity was 6.93E05 cm/s [13]. The default SESAME tabular EOS [11] was used for air which filled all empty space in the computational model.

The soil material models were rather difficult to select because of limited information available on dynamic soil properties of widely differing soil types at high strain r ates. Soil properties appear to vary considerably depending upon the location, type, moisture content, porosity, aggregate size, ambient temperature, and humidity conditions, etc. These property variations can significantly

affect the interacting loading mechanisms and generated load functions as well as the resultant structural response. Most dynamic soil equations of state are devoted to high compression regimes appropriate in underground tests, and very little information is available for soil models in tension or dilatation as occurs in shallow-buried mine explosions. Two different soil models i.e., completely dry sand and fully saturated wet sand were included for this investigation.

(a) Dry Sand

Sand is a porous aggregate of particles of various minerals, most commonly silica (fused quartz). The properties of sand can vary, depending on the degree of compaction, the types of minerals present, and the moisture content. In this study, fused quartz is the only mineral assumed to be present. The density of quartz sand is assumed to be 1.6 g/cc which corresponds to a porosity of 27.4%, assuming an initial density of 2.2 g/cc for solid silica.

For dry sand, a new Equation-of-State (EOS 7010) for fused quartz, which was recently developed by G.I. Kerley [14, 15] was used in this study. This new tabular EOS for the dry sand pressure-density relationship gave reasonably good agreement with Hugoniot experimental data [16] for dry sand. It gives correct density at low pressures and reproduces the phase transition in the pressure range. It is clearly a better model than the EOS 7100 in the "seslan" database file currently available in the CTH library which does not correlate well with the experimental Hugoniot data for dry sand. Time step instability problem in EOS 7100 was drastically reduced in the new EOS model by including Maxwell constructions that are necessary to model vaporization behavior.

The porous sand is not expected to support much elastic deformation or tension. Therefore only nominal values for the material strength and fracture parameters with a yield strength of 1.0E9 dynes/sq. cm, Poisson's ratio of 0.3 and a fracture strength of –1.0E6 dynes/sq.cm.

(b) Wet Sand

For a porosity of 27.4%, fully-saturated wet sand would have a composition of 85.5% silica and 14.5% water by weight and a density of 1.87 g/cc. An EOS table for this composition was constructed by G.I. Kerley [14] using the PANDA mixture model [15]. The procedure was similar to that used for dry sand except for the addition of water and hydrogen.

While the Hugoniots for wet sand (EOS table #7011) and dry sand (EOS table #7010) are very similar to each other in the pressure-density plane, the energy absorbed by wet sand is considerably lower than the energy of dry sand at the same shock pressure. Dry sand due to high porosity content is able to absorb more of the explosive energy than wet sand in a buried mine explosion. As a result, An explosion in wet sand more acceleration of the steel plate than in dry sand.

Due to high water content, wet sand would not be expected to support significant elastic deformation or tension. Therefore, the yield strength of wet sand was set to zero. Also wet sand was not allowed to fracture, since the EOS of fully saturated sand does not have a tension region, except at very low temperatures beyond the scope of the current study.

6

RESPONSE COMPUTATION

The simulation of the propagation of the explosive blast and soil products through the air and of the subsequent interaction with the steel plate was performed using the CTH hydrodynamic code. An initial time step of 1.0 μs was selected at the start of computation, and the response was tracked up to 2 ms, corresponding to approximately 2,000 computational cycles. A minimum time step of 0.01 μs was specified to avoid numerical instability.

Gravity effects were included in the simulation to duplicate actual experimental conditions. Active Lagrangian tracer particles were selected along the back surface and the horizontal midplane as well as the vertical axis of symmetry of the plate. The selection of tracer particles where history plots of position, velocity, pressure, and maximum principal stress as a function of time would be generated was guided by experimental considerations. The locations selected generally corresponded with locations where gauges were to be mounted.

History plots of vertical linear momentum trapped in the RHA steel plate were generated for later comparison with momentum measurements. Cross-sectional plots of blast-soil-structure interaction and target response were plotted at frequent time intervals. These graphical representations led to a better understanding of the loading mechanisms.

RESULTS AND DISCUSSION

Calculations were carried out with the Feb. 99 version of CTH. The modified dry and wet sand EOS routines provided by G.I. Kerley [13] were employed. The explosive was modeled as a disk of TNT, 30 cm in diameter and 8 cm in thickness, with no case. The initial explosive density was 1.60 g/cc and the corresponding explosive weight was 9050 gm (approximately 20 lb). The top of the explosive charge was 15 cm below the soil surface. The plate was 244 cm (8 ft) square and 20 cm t(approximately 8 in) thick. The RHA steel was 46 cm (18 in) vertically upward from the soil surface. Additionally, the center of the plate was offset 61 cm (24 in) horizontally from the center of the explosive charge as shown in Figure 1.

Cross-sectional plots of blast-soil-plate interaction revealed elongation of steel plate at bottom corners in spite of high elastic modulus and stiffness properties of the RHA steel. Corner deformation was found to be an artifact of the numerical code computation, occurring at or near the interface where a mesh containing a relatively stiff material is located next to a soft material. This condition caused uncontrolled material flow and leakage through corners along the interface. It was decided to use the boundary layer interface (BLINT) capability in the code along the interface between the hard RHA steel target and the relatively soft air medium to mitigate this problem. However, no significant change was observed in the resultant time history or cross-sectional plots due to use of the BLINT capability available in the hydrocode.

Computation using the 20-cm-thick anvil plate exhibited some transverse bending deformation, a typical cross-sectional view of which is shown in Figure 2. In addition to bending deformation, some angular rotation was observed due to asymmetric loading from explosive detonation in dry sand.
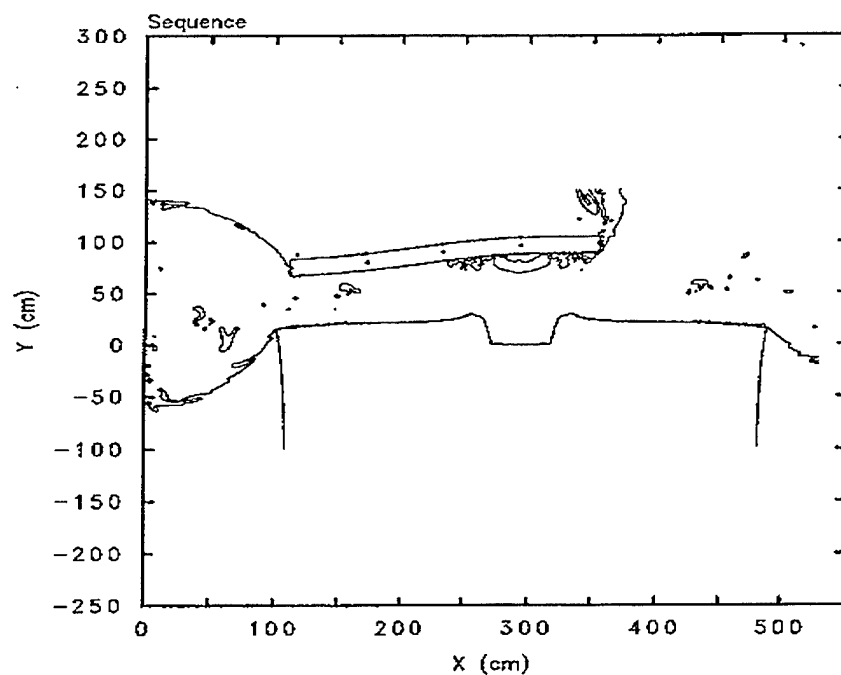
7

Figure 2. A Sectional View of the Mine-Soil-Plate Interaction at 2 ms for the 20-cm-Thick Plate

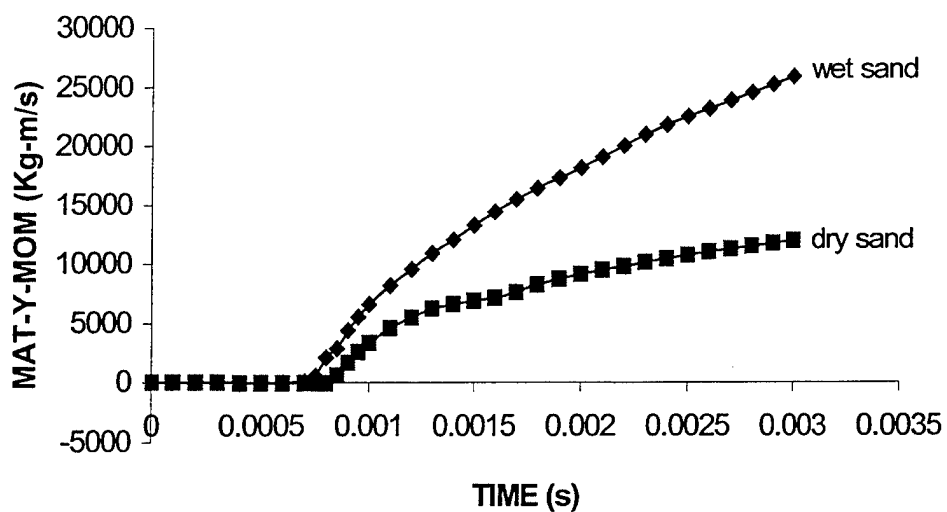**3D Asymm. mine-sand-plate analysis**

Figure 3. Comparison of Linear Vertical Momenta Trapped in the Steel Plate Due to Explosive Detonation in Dry vs. Wet Sand for the 3-D Asymmetric Mine-Soil-Structure Interaction Problem

A typical history plot of integrated linear momenta in the vertical Y direction for the steel plate is shown in Figure 3 The momentum is initially 0 for the first 0.5 ms until the arrival of the blast wave at the bottom interface of the plate. The momentum absorbed by the plate increases rapidly for the next 0.1 ms and then gradually for an additional 2.5 ms. Thereafter, it reaches a plateau before eventually decaying due to air drag and gravitational effects. Comparison of the anvil plate vertical momenta from detonation of a mine buried in fully saturated sand (shown as a curve joining filled diamonds) vs. dry sand (described by a curve joining square boxes) indicates considerably higher momenta for wet sand relative to dry sand attaining a peak differential of approximately 150%. This is significantly higher than results from 2-D plane strain model computation reported earlier [17]. It appears that 2-D models are relatively easy to set up and economical to run and the results are quite satisfactory for the axisymmetric case. However, for the asymmetric mine-soil-plate interaction problem, simplified 2-D models are inadequate to capture 3-D effects necessitating the use of 3-D modeling and analysis.

In the calculations for wet sand, the soil layer does not thin down as it does for dry sand. This is probably because wet sand is not porous and does not compress as much as dry sand when shocked. Porosity increases the Hugoniot energy at a given shock pressure, so that porous dry sand will absorb more of the explosive energy. Reduced porosity in wet sand results in less energy absorption and increased contribution to the impulse delivered to the plate. However, the large amount of momentum trapped in the anvil plate for the wet sand, approximately 2.5 times that for the dry sand could also be contributed by the sand layer in front of the expanding explosive reaction products which is thicker for wet sand than for the porous dry sand, which compresses much more upon shocking. Also wet sand remains cohesive for a considerable period of time before fragmentation and dispersion occur in the debris cloud, while lighter sand particles have low mass and momentum and tend to separate at early times Additionally, the increase in momentum could be enhanced by increased mass due to water in the sand and increased focussing effects of wet sand, as well as higher stiffness and shock speeds in the wet media. Further studies will be needed to determine which mechanisms have the most influence on structural loading due to explosive detonation in wet soil.

REFERENCES

1. Hanna, J. W. "An Effectiveness Evaluation of Several Types of Antitank Mines." BRL-MR-616, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1952.

2. Norman, R. M. "Deformation in Flat Plates Exposed to HE Mine Blast." AMSAA-TM-74, U.S. Army Materiel Systems Analysis Agency, Aberdeen Proving Ground, MD, 1970.

3. Hoskin, N. E., J. W. Allan, W. A. Bailey, J. W. Lethaby, and I. Skidmore. "The Motion of Plates and Cylinders Driven at Tangential Incidence." *Fourth International Symposium on Detonation,* ACR-126, Office of Naval Research, Pasadena, CA, 1965.

4. Dehn, J. T. "Models of Explosively Driven Metal." BRL-TR-2626, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1984.

5. Lottero, R. E., and K. D. Kimsey. "A Comparison of Computed Versus Experimental; Loading and Response of a Flat Plate Subjected to a Mine Blast." BRL-MR-02807, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1984.

6. Gupta, A. D. "Dynamic Analysis of a Plate Subjected to an Explosive Blast." *Proceedings of the ASME International Computers in Engineering Conference and Exhibition,* vol. 1, Boston, MA, 1985.

7. Gupta, A. D., F. H. Gregory, R. L. Bitting, and S. Bhattacharya. "Dynamic Analysis of an Explosively Loaded Hinged Rectangular Plate." *Computers and Structures,* vol. 26, pp. 339–344, United Kingdom: Pergamon Press Ltd., 1987.

8. Gupta, A. D., H. L. Wisniewski, and R. L. Bitting. "Response of a Generic Vehicle Floor Model to Triangular Overpressure Loads." *Computers and Structures,* vol. 32, no. 3/4, pp. 527–536, United Kingdom: Pergamon Press Ltd., 1989.

9. Gupta, A. D. "Dynamic Elasto-plastic Response of a Generic Vehicle Floor Model to Coupled Transient Loads." PVP-Vol. 351. *Structures Under Extreme Loading Conditions,* pp. 81-86, ASME, 1997.

10. McGlaun, J. M., S. L. Thompson, and M. G. Elrick. "CTH: A Three-Dimensional Shock Wave Physics Code." *International Journal of Impact Engineering,* vol. 10, nos. 1–4, pp. 251–360, 1990.

11. Hertel, E.S., and Kerley, G.I., "CTH Reference Manual: The Equation of State Package," Sandia National Laboratories Report SAND98-0947, Albuquerque, NM, 1998.

12. Johnson, G. R., and W. H. Cook. "A Constitutive Model and Data Subjected to Large Strains, High Strain Rates and High Temperatures." *Proceedings of the Seventh International Symposium on Ballistics,* pp. 541–547, The Hague, Netherlands, 1983.

13. Dobratz, E.M., and Crawford, P.C., "LLNL Explosives Handbook," Lawrence Livermore National Laboratory Report UCRL-52997, Livermore, CA, January 1985.

14. Kerley, G.I. "Equations of State for Composite Materials," Kerley Publishing Services Report KPS99-4, Albuquerque, NM, December 1999.

15. Kerley, G.I. "User's Manual for Panda II: A Computer Code for Calculating Equations of State," Sandia National Laboratories Report SAND88-2291, 1991.

16. Van Thiel, M. "Compendium of Shock Wave Data," Lawrence Livermore National Laboratory Report UCRL-50108, Rev.1, Livermore, CA, June 1977.

17. A.D. Gupta. "Modeling and Analysis of an Asymmetric Mine-Soil-Structure Interaction Problem, @ ASME Bound Volume, AStructures Under Extreme Loading Conditions, Bk. No. H0211, ASME PVP 98, New York, N.Y., July 1998.

INTENTIONALLY LEFT BLANK.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	OSD OUSD(A&T)/ODDR&E(R) DR R J TREW 3800 DEFENSE PENTAGON WASHINGTON DC 20301-3800
1	COMMANDING GENERAL US ARMY MATERIEL CMD AMCRDA TF 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN 3925 W BRAKER LN STE 400 AUSTIN TX 78759-5316
1	DARPA SPECIAL PROJECTS OFFICE J CARLINI 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	US MILITARY ACADEMY MATH SCI CTR EXCELLENCE MADN MATH MAJ HUBER THAYER HALL WEST POINT NY 10996-1786
1	DIRECTOR US ARMY RESEARCH LAB AMSRL D DR D SMITH 2800 POWDER MILL RD ADELPHI MD 20783-1197

NO. OF COPIES	ORGANIZATION
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CI AI R 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI IS T 2800 POWDER MILL RD ADELPHI MD 20783-1197

ABERDEEN PROVING GROUND

2	DIR USARL AMSRL CI LP (BLDG 305)

13

NO. OF COPIES	ORGANIZATION	NO. OF COPIES	ORGANIZATION
1	PM TMAS SFAE GSSC TMA SMD R KOWALSKI PICATINNY ARSENAL NJ 07806-5000	1	NSWC CRANE DIV M JOHNSON CODE 2OH4 LOUISVILLE KY 40214-5245
3	PEO FIELD ARTILLERY SYS SFAE FAS PM H GOLDMAN T MCWILLIAMS T LINDSAY PICATINNY ARSENAL NJ 07806-5000	1	DAVID TAYLOR RES CTR SHIP STRCTRS & PROT DEPT J CORRADO CODE 1702 BETHESDA MD 20084
1	PM CRUSADER G DELCOCO J SHIELDS PICATINNY ARSENAL NJ 07806-5000	2	DAVID TAYLOR RES CTR R ROCKWELL W PHYILLAIER BETHESDA MD 20054-5000
2	NASA LANGLEY RES CTR AMSRL VS W ELBER F BARTLETT JR MS 266 HAMPTON VA 23681-0001	1	DNA INNOVATIVE CONCPTS DIV R ROHR 6801 TELEGRAPH RD ALEXANDRIA VA 22310-3398
2	COMMANDER DARPA J KELLY B WILCOX 3701 N FAIRFAX DR ARLINGTON VA 22203-1714	1	EXPEDITIONARY WARFARE DIV N85 F SHOUP 2000 NAVY PENTAGON WASHINGTON DC 20350-2000
6	COMMANDER WRIGHT PATTERSON AFB WL FIV A MAYER WL MLBM S DONALDSON T BENSON TOLLE C BROWNING J MCCOY F ABRAMS 2941 P ST STE 1 DAYTON OH 45433	1	OFC OF NAVAL RESEARCH D SIEGEL 351 800 N QUINCY ST ARLINGTON VA 22217-5660
		2	NSWC R HUBBARD G633 C DAHLGREN DIV DAHLGREN VA 22448
1	OFFICE OF NAVAL RESEARCH MECH DIV CODE 1132SM Y RAJAPAKSE ARLINGTON VA 22217	7	NSWC J H FRANCIS CODE G30 D WILSON CODE G32 R D COOPER CODE G32 E ROWE CODE G32 J FRAYSSE CODE G33 T DURAN CODE G33 L DESIMONE CODE G33 DAHLGREN VA 22448
		1	COMMANDER NAVAL SEA SYS CMD D LIESE 2531 JEFFERSON DAVIS HWY ARLINGTON VA 22242-5160

NO. OF COPIES	ORGANIZATION
1	DIR USARL AMSRL CP CA D SNIDER 2800 POWDER MILL RD ADELPHI MD 20783
1	COMMANDER US ARMY ARDEC AMSTA AR FSE T GORA PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER US ARMY ARDEC AMSTA AR TD R PRICE V LINDNER C SPINELLI PICATINNY ARSENAL NJ 07806-5000
5	COMMANDER US ARMY TACOM AMSTA JSK S GOODMAN J FLORENCE AMSTA TR D R GONZALEZ D TEMPLETON D OSTBERG WARREN MI 48397-5000
1	COMMANDER US ARMY ARDEC SFAE FAS PM F MCLAUGHLIN PICATINNY ARSENAL NJ 07806-5000
5	COMMANDER US ARMY ARDEC SFAE GCSS SD COL B ELLIS M DEVINE W DEMASSI J PRITCHARD S HROWNAK PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
4	COMMANDER US ARMY ARDEC AMSTA AR CCH S MUSALLI R CARR M LUCIANO T LOUCEIRO PICATINNY ARSENAL NJ 07806-5000
4	COMMANDER US ARMY ARDEC AMSTA AR (2 CPS) E FENNEL (2 CPS) PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR CCH P J LUTZ PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR FSF T C LIVECCHIA PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR QAC T C C PATEL AMSTA AR ASL B WILLIAMSON PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR M D DEMELLA F DIORIO PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
3	COMMANDER US ARMY ARDEC AMSTA AR FSA A WARNASH B MACHAK M CHIEFA PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER SMCWV QAE Q B VANINA BLDG 44 WATERVLIET ARSENAL WATERVLIET NY 12189-4050
1	COMMANDER WATERVLIET ARSENAL SMCWV SPM T MCCLOSKEY BLDG 253 WATERVLIET NY 12189-4050
8	DIRECTOR BENET LABORATORIES AMSTA AR CCB J KEANE J BATTAGLIA J VASILAKIS G FFIAR V MONTVORI G DANDREA R HASENBEIN WATERVLIET NY 12189
1	COMMANDER WATERVLIET ARSENAL SMCWV QA QS KINSCO WATERVLIET NY 12189-4050
1	COMMANDER US ARMY ARDEC PRDCTN BASE MODERN ACTY AMSMC PBM K PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY BELVOIR RD&E CTR STRBE JBC FT BELVOIR VA 22060-5606

NO. OF COPIES	ORGANIZATION
2	COMMANDER US ARMY ARDEC AMSTA AR FSB G M SCIUKSNIS D CARLUCCI PICATINNY ARSENAL NJ 07806-5000
1	US ARMY COLD REGIONS RSCH & ENGR LABORATORY P DUTTA 72 LYME RD HANOVER NH 03755
1	DIR USARL AMSRL WT L D WOODBURY 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	COMMANDER US ARMY AMCOM AMSMI RD W MCCORKLE AMSMI RD ST P DOYLE AMSRI RD ST CN T VANDIVER REDSTONE ARSENAL AL 35898-5247
5	US ARMY RESEARCH OFFICE A CROWSON J PRATER R SINGLETON G ANDERSON K IYER PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211
5	PROJECT MANAGER TANK MAIN ARMAMENT SYS SFAE GSSC TMA COL PAWLICKI K KIMKER E KOPACZ R ROESER B DORCY PICATINNY ARSENAL NJ 07806-5000

ABERDEEN PROVING GROUND

9   DIR USARL
       AMSRL WM TD
         R BITTING (2 CPS)
         F GREGORY (2 CPS)
         N GNIAZDOWSKI (2 CPS)
         A DAS GUPTA (2 CPS)
         A DIETRICH

INTENTIONALLY LEFT BLANK.

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project(0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2001	Reprint, October 1999–December 2000

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Modeling and Analysis of a 3-D Asymmetric Mine-Soil-Hull Floor Interaction Problem With Mine Buried in Dry and Wet Sand	1L162618AH80

6. AUTHOR(S)

Aaron D. Gupta

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
U.S. Army Research Laboratory ATTN: AMSRL-WM-TD Aberdeen Proving Ground, MD 21005-5066	ARL-RP-29

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)	10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

A reprint from Proceedings of the 71st Shock and Vibration Symposium, Shock and Vibration Information Analysis Center, Arlington, VA, 6–9 November 2000.

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution is unlimited.	

13. ABSTRACT (Maximum 200 words)

An above-ground 2.44 m × 2.44 m × 20 cm rolled homogeneous armor (RHA) plate with a total mass of 9000 kg located asymmetrically at a fixed horizontal 61 cm offset and a vertical 46 cm stand-off above a shallow-buried mine with an equivalent charge weight of 9.05 kg TNT and 15 cm depth of overburden in dry and wet sand has been modeled in 3-D using the CTH hydrodynamic code. The purpose is to compare the loading and response of the anvil plate due to detonation of a mine buried in dry and wet sand using a 3-D asymmetric model of a mine-soil-hull floor interaction problem. The model allows parametric study of complex explosive-soil-structure interaction effects due to variation of explosive types and plate dimensions, standoff, types of soil and height of soil overburden and computes momentum loading on the ballistic pendulum anvil plate due to various off-axis locations of the mine in dry and wet soils relative to the hull floor plate located on the underside of an armored vehicle.

14. SUBJECT TERMS		15. NUMBER OF PAGES
3-D asymmetric, mine-soil-structure interact, RHA plate, buried mine, dry and wet sand, vertical momentum		19
		16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

INTENTIONALLY LEFT BLANK.